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A Two-Stage Volunteer Assignment Model for Post-Disaster Search and Rescue Operations

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Abstract

Effective volunteer management requires ensuring operational continuity and maximizing benefits from all team members. Prioritizing volunteers with adequate knowledge and experience in task assignments is crucial for maintaining workflow continuity. This study employs a two-stage model for allocating areas and tasks to volunteers in search and rescue operations. The first stage identifies the optimal number of volunteer response centers using the P-median problem. Considering population density as demand, 7 out of 14 accessible and protected disaster collection areas meeting basic needs are selected as optimal response centers based on distance. In the second stage, a mixed-integer programming model is proposed for volunteer assignment, which prioritizes assigning the most knowledgeable and experienced volunteers to critical positions. The model's flexibility and applicability are demonstrated by incorporating voluntary rest periods, which are allocated based on the urgent needs of response centers in various post-disaster scenarios. Solved using GAMS/CPLEX, the model's results show that expert volunteers in low-demand scenarios are prioritized, working 5 out of 9 shifts, while other volunteers receive insufficient assignments. In high-demand scenarios, some response centers face volunteer shortages, with a deficit of 62 volunteers across 9 shifts in non-emergency areas. The study evaluates the benefits and drawbacks of the volunteer assignment model and offers recommendations for future research.

Keywords: Volunteer response center, P-median, Volunteer assignment model

1. Introduction

Natural disasters such as earthquakes, floods, and landslides, along with human-made disasters like war, nuclear, and chemical accidents, cause substantial damage to nations, affecting both their physical and mental well-being. An example of this is the earthquake that occurred in Turkey on February 6, 2023, which resulted in a death toll of over 48,000, destroyed more than 500,000 buildings, and caused many people to lose their jobs and relatives [1]. Disaster management minimizes the impact of such large-scale earthquake-like disasters through four stages: preparedness (risk identification and planning), mitigation (loss prevention), response (emergency response during the disaster), and recovery (restoration of infrastructure and living conditions). Effective personnel management is also crucial for reducing or mitigating the impact of such disasters and minimizing the resulting significant losses. By focusing on evacuation points and personnel deployment during the disaster preparation phase, effective disaster management can be ensured during the disaster response phase, thereby reducing the disaster's impact [2]. In case of a disaster, immediate search in the response phase, and rescue efforts along with initial medical assistance, should be prioritized, followed by addressing shelter and nutritional requirements. After any disaster, local and international volunteer organizations and professionals mobilize swiftly to address urgent needs. Following the earthquake in Turkey, 36,527 volunteers, along with numerous expert personnel, were involved in the relief operations [3]. However, managing a volunteer group is different from managing professional staff. Since volunteers work without financial incentives, assigning them tasks according to their appropriate periods and abilities is important.

When assigning tasks to volunteers based on their abilities, it is crucial to maintain consistency within the organisation by prioritising their satisfaction and skills, in contrast to the approach taken with professionals. Disregarding the individual characteristics of volunteers and assigning tasks without considering their skills and expertise can lead to significant disruptions in workflow, lower morale, and satisfaction levels among volunteers, and potentially result in them discontinuing their duties [4]. Hence, when assigning volunteers to roles within an organization, their knowledge and skills should be assessed and matched accordingly. Priority in task allocation should be given to the volunteer group with the highest level of expertise. Providing the personnel needs primarily from the expert team will ensure that the work in the organisation is conducted in the best possible way without any disruption. Amini et al. [5] study of disaster response in Iran found that training volunteers to improve their knowledge, skills, and attitudes increased their expertise, leading to more effective and efficient disaster response operations compared to a group that received no training.

Identifying appropriate service locations is just as critical as assigning suitable tasks to volunteers. It is of vital importance that personnel who will take part in disasters reach their place of duty promptly. When disasters occur, safe areas are needed to ensure the immediate safety of the people affected. To meet this need, disaster collection areas have been determined before any type of disaster in Turkey. The purpose of these areas has been determined as the closest accessible area where the victim can meet their basic needs and be away from danger after any disaster [6]. Identifying volunteer response centers through these designated gathering areas will help volunteers reach disaster victims faster and convey requests from victims to the center promptly.

This study aims to optimize disaster response by strategically positioning volunteers before disasters and allocating tasks effectively during the response. It addresses two fundamental questions: "How can the number and location of volunteer response centers be optimized?" and "How can volunteers with varying expertise be assigned to centers with different urgency

levels, considering constraints?" To address these research questions, the study proposes a two-stage volunteer assignment model. In the first stage, the volunteer location problem is addressed using the P-median problem for disaster preparedness management. In the second stage, an assignment model based on experience-urgency matching is used to optimize volunteer task assignments tailored to real-world scenarios (high demand, variable demand, and low demand) by considering the urgency status at these designated locations, thereby aiming to improve disaster response. The proposed volunteer assignment model aims to make the following contributions to the literature:

- Employing a p-median model for volunteer allocation to response centers in disaster preparedness
- Proposed a mixed integer model that incorporates volunteer preference and rest periods for task allocation during disaster response
- Prioritizing high-skilled volunteers for high-urgency centers based on expertise
- Demonstrating and analyzing model performance in realistic post-disaster scenarios under varying demand and urgency conditions.

The rest of this paper is structured as follows: the literature review is analysed in the next section. In section three, volunteer response centers are designated based on disaster collection areas. The centers are selected from reliable, accessible locations that meet basic needs, guided by the P-median problem. In addition, a task assignment model is developed to efficiently allocate responsibilities among volunteer groups in gathering areas. The model prioritizes tasks for the most experienced volunteers based on the demands and urgency of the response centers, while considering each volunteer's experience level and work-rest cycles, using mixed-integer programming. To demonstrate the model's applicability, volunteer personnel from search and rescue teams are assigned based on various post-disaster scenarios in section four. The final section evaluates the volunteer assignment model used in these scenarios and suggests improvements for future research.

2. Literature Review

2.1 P Median Problem

The P-median problem, a facility location selection method introduced by Reville and Swain [7], has been applied across diverse fields. These include emergency room placement in healthcare, facility location optimization based on customer demand in retail and logistics, and multi-objective optimization for coverage and service levels in healthcare and emergency services. The improved p-median problem also incorporates advanced metaheuristics, matrix decompositions, and heuristic/hybrid methods [8].

The p-median problem helps determine optimal locations for disaster collection areas, particularly when demand is high during disaster management. Several studies have employed the P-median model for locating disaster relief facilities. For example, Pan [9] used it to optimize typhoon emergency shelter placement in coastal rural China, while Xi et al. [10] modified the model to account for rescue time constraints in a Western China neighbourhood. Zhu et al. [11] presented a robust P-median model incorporating scenario analysis for uncertain disaster area prediction. More recently, Hwang and Geo [12] used the algorithm to locate shelters, supply depots, and control centers around the Kori nuclear site, and Ayudhya [13,14] employed it to identify flood shelter locations in southeastern Thailand and relief facility locations on Thailand's east coast, respectively. Similarly, Eliguzel [15] optimized emergency operation center allocation in the Philippines using a weighted P-median approach with Pictorial Fuzzy.

2.2 Volunteer assignment model:

The volunteer assignment model first introduced by Falasca and Zobel [16] is a bi-criteria integer programming model designed to minimize planning costs while adhering to volunteers' preferences to avoid undesirable assignments. Table S.1 (in the Supplementary file) provides a chronological summary of volunteer assignment models across four key aspects[17]. The

columns detail: 1) objective functions (maximizing or minimizing utility based on shortage, undesired assignment, and time); 2) constraints considered (task, preference, shifts, skills, and travel); 3) solution methods employed (integer, goal, heuristic, and artificial intelligence); and 4) shortcomings identified in the studies (daily wage, demand, application area, or travel time).

When voluntary assignment models are examined in terms of their solution methods, some studies employ integer programming models; however, existing approaches have limitations. García et al. [18] maximized volunteer benefits and minimized costs, yet their model struggles with complex scenarios and lacks clear optimization strategies. Kaur et al. [19] balanced several factors to improve retention but recognized limitations in volunteer participation and diversity. Chen et al. [20] optimized volunteer dispatch in emergencies but highlighted the need for better task coordination. Atik et al. [21] maximized demand served and minimized travel costs, while neglecting key factors such as transportation costs and stochasticity.

Mathematical modelling of volunteer assignment problems has been approached in several ways. Degel et al. [22] minimized the number of fire stations based on volunteer availability and travel times, but did not consider volunteer schedules, per diem, or uncertain rescue demand. Lassiter et al. [23] dynamically allocated volunteers to minimize unmet task demands, assignment costs, and skill mismatches, achieving a Pareto optimum through a constrained allocation model. Urrea et al. [24] optimized pairings of experienced and inexperienced volunteers but neglected organizational financial or time contributions. Wang et al. [25] categorized and ranked risk areas for emergency supply distribution and modelled volunteer deployment but did not consider multi-hour cost functions or volunteer substitution.

Heuristic methodology has also been used in some studies for the volunteer assignment model. Abualkhair et al. [26] used a simulation to minimize arrival and service times in a two-queue system for donors and donations but ignored heterogeneity and uncertainty. Paret et al. [27] developed a multi-server queuing model to manage the spontaneous volunteers who emerged after the disaster, but not training/skills. Fei and Wang [28] applied the Dempster-Shafer theory to optimize rescuer dispatch, which needs broader analysis. Xue et al. [29] applied the same theory to consider the volunteers' abilities, task demands in disaster areas, and waiting time, while development is needed for estimating the time in both the disaster and dispatched areas. Matinrad and Granberg [30] minimized start times, but their model assumed uniform skills and did not account for travel, task transfer, or equipment installation times. Ata et al. [31] investigated the dynamic control of the system by formulating a multi-class queuing network model to maximize volunteer efficiency. Kapukaya and Satoglu [32] developed a two-stage stochastic programming model for optimising resource allocation in search and rescue efforts, but it should also apply to other disasters and missions and consider longer time horizons to address resource allocation during recovery. Karahalios et al. [33] used a novel two-level nested heuristic called the Graver Augmented Multiple Seed Algorithm (GAMA) to solve the problem by formulating the first response network design problem (FRNDP) as a mixed integer nonlinear program.

In addition to these solution methods, Aman et al. [34] developed a goal-programming volunteer assignment model that minimizes penalty costs associated with volunteer numbers, shift changes, and task deviations; however, this model neglects volunteer preferences and unused workforce. Rabiei et al. [35] used NSGA-II and NREGA, neural networks in artificial intelligence, to assign volunteers considering their abilities, preferences, and task demands, but the application of their model is limited to nursing, and its performance has not been compared against other algorithms.

According to the data obtained from the literature analysis, there is one research on a two-stage volunteer assignment model [32]. To address the gap, this study introduces a two-stage disaster management model, optimizing response center locations and volunteer assignment across preparation and response phases. While skills-based volunteer deployment has been explored in some studies [19, 23, 25, 32], this model incorporates expert-emergency area

matching based on regional urgency. Some models address disaster implementation [20,21,30], but they lack studies on diverse disaster scenarios. This study analyses model applicability through realistic disaster scenarios and designs volunteer emergency response plans based on expert personnel needs. Furthermore, it prioritizes volunteer satisfaction by including rest period restrictions, an aspect overlooked in previous research. This paper distinguishes itself through contributions in the following areas:

The proposed two-stage model handles both location and task distribution.

- Volunteer response centers in disaster areas will be chosen from the best locations using the P median problem before assigning volunteers.
- Task allocation will prioritize experienced volunteers by using groups with tiered expertise.
- Volunteer assignment priority will be determined based on the urgency of the response centers' needs.
- The model's validity will be assessed using a group of volunteers involved in search and rescue, evaluated with scenarios simulating post-disaster conditions.
- Volunteers will be given designated rest periods to prevent consecutive shifts.

3. Methodology

Immediate intervention in disaster areas is crucial to alleviate chaos, minimize risks, and optimize the use of personnel. Establishing operational centers and pre-determining intervention areas facilitates access, prevents disorder through effective volunteer distribution, and ensures optimal working conditions. Deploying volunteer to these designated areas enhances intervention capability and ensures their safety. When distributing tasks to volunteers, their knowledge and experience levels are taken into consideration. Assigning volunteers with the highest level of knowledge to risky tasks ensures that task distribution is planned effectively and that volunteers remain within the organization. This research is designed with this aim in mind, and the implementation stages are summarized in **Figure 1**.

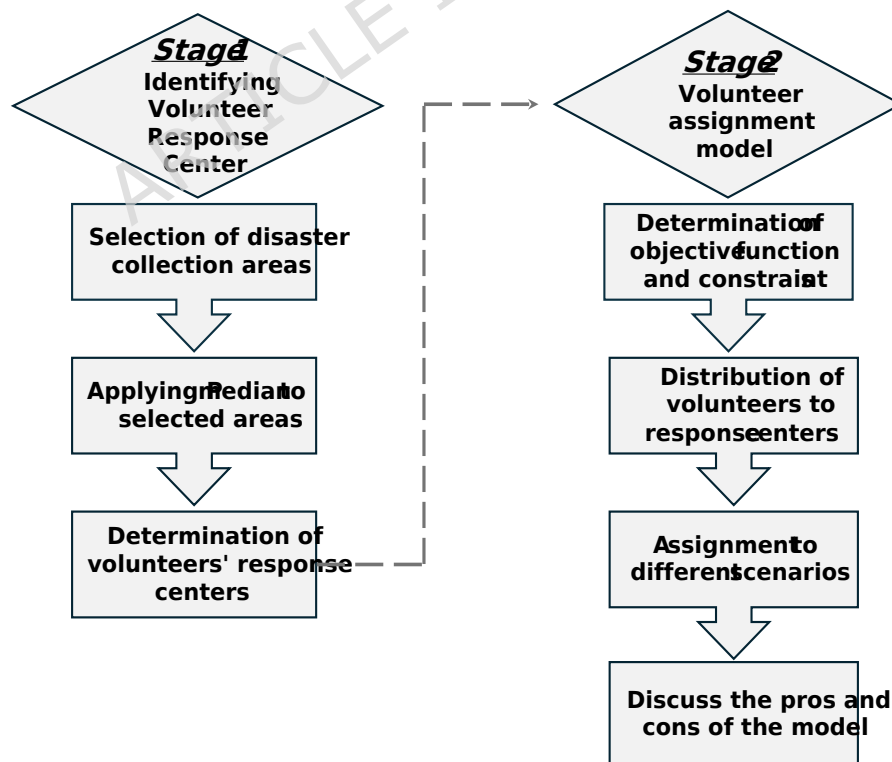


Figure 1. Developed two stages of the volunteer assignment model.

In the first stage of the proposed approach, an optimum number of volunteer response centers are selected from among the pre-disaster collection areas (candidate locations) determined by AFAD, taking into account the centers' needs and distances from other centers, using the P-

median problem. These centers should be easily accessible, away from risks and structures, and equipped to meet basic needs [36]. The aim is to guarantee a rapid response to every disaster area by ensuring the shortest possible access time to all centers.

In the second stage of the proposed approach, a volunteer assignment model is developed to meet the demands and urgency of the designated volunteer response centers. The main goal of the model is to ensure that volunteers with the highest level of knowledge are assigned to the most critical regions. When distributing tasks, the principle of not assigning consecutive shifts is applied, taking work and rest periods into account. Different disaster scenarios are used during task distribution, aiming to meet the demands and urgency levels of each volunteer center. The AFAD Volunteers Club (AFC) selected for the proposed assignment model was included in this study after being informed and providing consent in accordance with guidelines and regulations and was informed about potential disaster response task assignments. The study concludes with a detailed analysis of the results from these scenarios, discussing the advantages and limitations of the model. The methods and formulas used in the study are summarized below.

3.1 P-median Problem

P-median, proposed by Reville and Swain [7], is a location selection problem aiming to find the location of p facilities using n nodes in a network to minimise the total average weighted distance between the demand and the facility. Unlike p -center problems that minimize maximum distance and capacity-oriented problems that balance capacity and costs, the p -median problem focuses on minimizing total demand distance or cost. This is particularly useful in disaster management, where maximizing the response area takes precedence over minimizing individual distances or coverage. By establishing response centers in high-demand areas and deploying resources, the p -median approach creates a service network with minimal distance, optimizing equipment operations with limited resources. It can also be used for logistical services like food aid and evacuation [37]. Despite its advantages, the p -median problem is NP-hard, requiring heuristic and meta-heuristic algorithms for all but very small-scale problems. This study will not be subject to the limitations of the method because it will prefer the P-median problem to determine the optimum number of facilities p (relative to demand and distance) among 14 small-scale regions, taking into account population densities, demand, and distances to these points.

The mathematical notation (Table 1) and formulation of the P-median problem is presented in Equations (1)– (5).

Table 1. Notation of the P -Median problem

Sets	
i	Demand points ($i = 1, \dots, n$)
j	Candidate facility location ($j = 1, \dots, n$)
Parameters	
d_{ij}	Distance demand points i location j
a_i	Demand weight i
p	Number of facilities
Decision Variable	
x_{ij}	1, If the demand point of i is assigned to facility j , otherwise 0
y_j	1, If the facility j is opened, otherwise 0

Objective function (1) seeks to minimize the total cost associated with service facilities and demand points by fulfilling all demands at the shortest possible distance. The cost is based on the distance from the request point to the facility.

$$\min \sum_{i=1}^n \sum_{j=1}^n a_i d_{ij} x_{ij} \quad (1)$$

Equation (2) guarantees that each demand point is assigned to a single facility, ensuring all demands are met with a minimal facility.

$$\sum_{j=1}^n x_{ij} = 1, \quad i = 1, 2, \dots, n \quad (2)$$

Equation (3) ensures that the demand point is not assigned to unsuitable facilities, preventing undesirable location selection.

$$x_{ij} \leq y_j, \quad i, j = 1, 2, \dots, n \quad (3)$$

The number of facilities to be opened is determined with the help of Equation 4. Thus, it limits the number of facilities to be used to meet the demands of p units.

$$\sum_{j=1}^n y_j = p \quad (4)$$

The last equation meets the integer and binary requirements for demands and facility openings.

$$x_{ij}, y_j \in \{0, 1\} \quad i, j = 1, 2, \dots, n \quad (5)$$

3.2 The Proposed Mathematical Model for Volunteer Assignment

After analysing volunteer assignment models in the literature, this study aims to develop a mixed integer programming model. This model is an improved volunteer assignment model that is based on the principle of maximum benefit, aims to assign the most experienced volunteers to the most critical region, and allows volunteers to rest after their working hours. The parameters, datasets, and decision variables of the developed assignment model, along with objective functions and constraints, are presented in Table 2.

Table 2. Notation of the proposed assignment model

Sets	
i	Volunteers ($i = 1, \dots, v$)
j	Volunteer's response center ($j = 1, \dots, l$)
t	Shift period ($t = 1, \dots, m$)
Parameters	
W_{jt}	Level of urgency in the response center j at time t ($W_{jt} \in \{0, 1, 2, 3, 4\}$)
C_i	Categories of volunteer i based on their level of expertise ($C_i \in \{1, 2, 3, 4\}$)
A_{jt}	Volunteer demand at the volunteer response center j at time t
Decision Variable	
x_{ijt}	1 If volunteers i assigned in period t , at location j , otherwise 0

The proposed mathematical model is given as follows:

Objective Function

$$\max \sum_{t=1}^{t=m} \sum_{j=1}^{j=l} \sum_{i=1}^{i=v} W_{jt} C_i x_{ijt} \quad (6)$$

Subject to

$$\sum_{j=1}^{j=l} A_{jt} \leq \sum_{j=1}^{j=l} \sum_{i=1}^{i=v} x_{ijt} \quad \forall t \in T \quad (7)$$

$$\sum_{j \in L} x_{ijt} \leq 1 \quad \forall i \in V, \forall t \in T \quad (8)$$

$$\sum_{j \in L} \sum_{t=k}^{t=k+1} x_{ijt} \leq 1, \quad \forall i \in V, k = \{1, 2, \dots, t-1\} \quad (9)$$

$$x_{ijt} \in \{0,1\}, \quad \forall i \in V, \forall j \in L, \forall t \in T \quad (10)$$

The objective function (6) aims to fulfil volunteer needs primarily by using highly skilled volunteers and allocating those with the highest expertise to the most critical regions based on urgency. Thus, it maximizes the weighted sum of assignments, and the weights combine volunteer expertise and central urgency. The proposed model includes 4 constraints. The first constraint (7) ensures that response centers are not assigned more volunteers than the number of volunteers needed in each period. Constraint (8) ensures that volunteers are assigned to only one response center per period. Constraint (9) ensures that there must be at least one rest period between working periods. Constraints (10) ensure that the assignment model is integer, non-negative, and binary.

4. Application

Distributing a classified volunteer group to specific areas helps prevent post-disaster chaos and enables faster response. However, the selected areas must be easily accessible, safe, and capable of meeting basic human needs [38]. Therefore, when selecting volunteer response centers, an analysis is required beforehand to ensure these conditions are met. In the implementation phase of this study, volunteer response centers are chosen from disaster collection areas with the specific features outlined by Tunceli Afad [39] in each neighbourhood within the main area of Tunceli province. Task distribution is then conducted using an assignment model that incorporates the rest periods of the Munzur Emergency Disaster Club, whose members voluntarily participated in emergency disaster response activities and served in various roles at these selected centers.

4.1 Volunteer Response Center

Tunceli province and its central neighbourhoods (Figure 2), situated in the Upper Euphrates Basin of the Eastern Anatolia Region, have experienced numerous natural disasters over time due to their geological structure, topography, tectonic activity, and weather conditions [40].

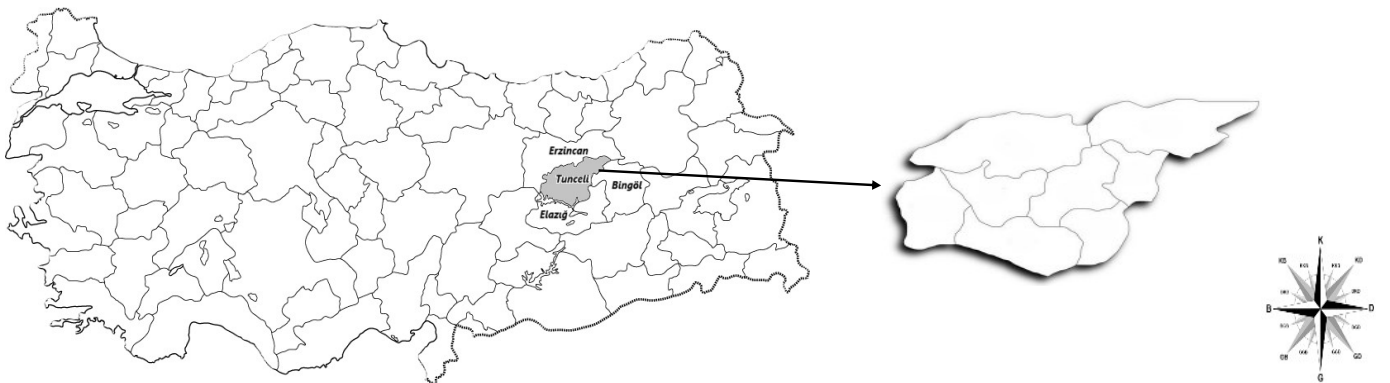


Figure 2. Tunceli province location and central neighbourhoods on the map of Turkey

Studies conducted for disaster risk reduction have identified protected areas against earthquakes, floods, and fires to cater to the personal needs of residents in every province and district. These designated areas aim to ensure the safety and well-being of individuals post-

disaster. Figure 3 illustrates the map showing the 14 disaster collection areas [38] designated for the 7 neighbourhoods in the center of Tunceli chosen for our research.



Figure 3. Tunceli central neighbourhoods' disaster-gathering areas

*Note: Figure 3 is created by adding disaster assembly area locations and descriptions to the original physical map using Google Maps Pro. (URL:

<https://www.google.com/maps/d/edit?hl=tr&mid=1NAgyfy4M1c6Lxc0S3PJRknpTVGrc-2U&ll=39.09738686940235%2C39.55959764999997&z=12>)

In the initial phase of our research, the volunteer response centers will be chosen from 14 predetermined disaster collection areas. The P median problem will minimise travel time among all gathering points and center distances. To address this obstacle, the distances from disaster collection areas to district centers with populations are provided in **Table 3**. These distances were calculated by measuring the road travel distance from public service offices located in neighbourhood centers to each disaster collection area using Google Maps.

Table 3. Distances (km) of district centers (with population in parentheses) to disaster collection areas.

<i>Center</i>	1	2	3	4	5	6	7	8	9	10	11	12	13	14
<i>District</i>														
<i>Aktuluk (1,934)</i>	11.4	8.6	16.5	11.9	7.4	6.8	10.9	4.8	6.7	1.2	9.8	11.2	11.2	11.9
<i>Alibaba (2,077)</i>	1.0	3.4	7.0	0.3	5.1	5.3	1.5	7.2	5.6	11.2	2.0	0.55	1.8	1.5
<i>Atatürk (22,102)</i>	5.3	2.5	10.3	5.7	1.8	1.2	4.8	1.6	0.26	5.7	3.7	5.0	5.1	5.9
<i>Cumhuriyet (5,201)</i>	1.9	1.8	7.3	2.2	3.6	3.8	1.8	5.6	4.1	9.6	0.9	1.6	2.1	2.9
<i>Esentepe (983)</i>	1.1	3.3	6.7	1.2	5.1	5.2	1.3	7.1	5.5	11.1	2.5	1.4	1.5	0.17
<i>İsmet İnönü (1,012)</i>	3.6	4.7	3.2	3.7	6.3	6.7	2.4	8.5	7.0	12.5	4.0	3.6	2.1	3.8
<i>Moğultay (2,548)</i>	0.3	2.8	6.4	0.75	4.6	4.8	0.9	6.6	5.1	10.6	1.8	0.7	1.2	1.0
<i>Yeni Mahalle (746)</i>	1.2	3.6	7.2	0.6	5.3	5.6	1.7	7.4	5.9	11.4	2.6	1.2	2.0	2.0

Using the population density and the distance data of the gathering areas to each district center, the P-median problem solution, indicating the number and specific center, is promptly computed using the GAMS/CPLEX solver with an Intel i5 11th Gen (2.40 GHz) 8 GB RAM processor, as illustrated in **Figure 4**. It suggests opening 7 centers 1, 4, 9, 10, 11, 13, and 14, where 'p' represents the number of centers opened (x-axis) and the product of total demand and distance(y-axis).

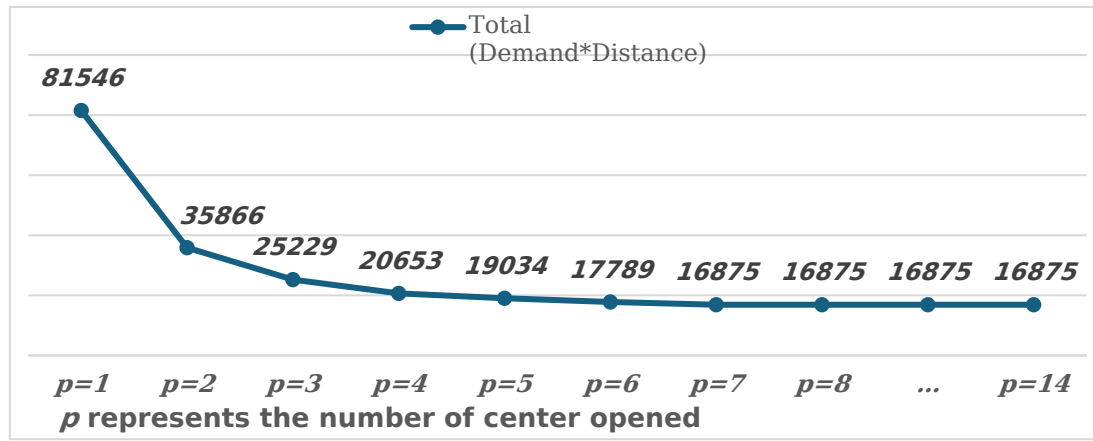


Figure 4. Number and distance of centers opened due to the P-median problem.

The expense of setting up volunteer response centers isn't factored into this model, as these centers aid in coordinating volunteers for search and rescue efforts. Opting for 14 volunteer response centers is not favoured as it could lead to excessive personnel dispersion, hampering communication and coordination.

4.2 Assigning volunteers to response centers

4.2.1 Volunteer selection and classification

The AFAD Volunteers Club (AFC), established by the Munzur University Department of Emergency Aid and Disaster Management, is a volunteer-oriented community dedicated to providing pre- and post-disaster assistance. In this paper, the volunteer assignment model is employed to determine the duty locations and working periods of volunteers in the club under various scenarios, both before and after the disaster in Tunceli province. The classification levels of volunteers according to their knowledge and experience in disasters were taken from the papers conducted. Their by Ozdemir et al. [42,43]. Their studies categorized disaster management volunteers into four classes: expert (C_1), experienced(C_2), sufficient(C_3), and inadequate (C_4) based on their competencies in search and rescue. This classification, determined using the TOPSIS-Sort method and weighted criteria from expert surveys, primarily aims to identify the most prepared volunteers for specific needs and planning. Nine criteria were considered, including first aid, teamwork, and search and rescue equipment skills. To optimize volunteer utilization and minimize risks, the expert group receives priority in task assignments. Volunteers in the inadequate category will be assigned basic tasks like food distribution or communication with victims or can be assigned more specialized tasks after sufficient training. This will allow them to specialize in professional operations such as first aid or search and rescue through pre-disaster training and drills. **Figure 5** illustrates the distribution of 124 volunteers across these classes resulting from the study. This volunteer pool forms a data set (i) for the proposed assignment model, while volunteer class levels are used in the model parameter (C_i) to match the intervention center urgency with the volunteer class level in the objective function.

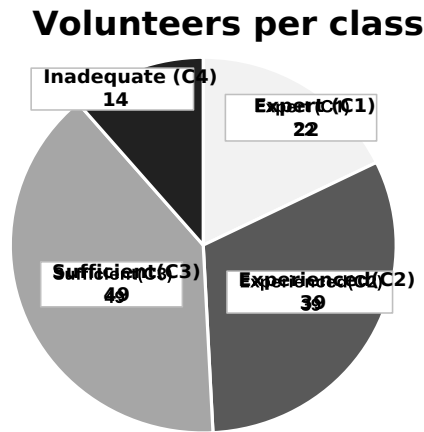


Figure 5. The classes and numbers of volunteers involved in search and rescue operations.

4.2.2 Parameter setting and justification

To effectively manage the varying levels of volunteer support needed in the aftermath of a disaster, the assignment model will incorporate a framework consisting of three distinct and defined scenarios. These scenarios are designed to represent the different phases and challenges encountered in post-disaster response efforts. A detailed overview of the specific requirements for each scenario, including key factors such as the expected demand for volunteers and the overall urgency of the situation, is provided in **Table 4**. This table offers a comprehensive summary of the demand and urgency parameters applicable to each scenario, enabling the volunteer assignment model to accurately allocate personnel according to the characteristics of each post-disaster phase.

The assignment model will assign values ($C_1 = 4, C_2 = 3, C_3 = 2, C_4 = 1$) to 124 volunteers, categorized into the top group (C_1) to the bottom group (C_4), based on their knowledge and experience levels. These volunteer class values are then multiplied by the volunteer response center urgency level in the proposed model's objective function (6) to maximize the matching of expert volunteers to the most urgent needs. Response center urgency levels (w_{jt}) range from 0 to 4, reflecting regional personnel needs: 0 (very safe): no volunteers needed; 1 (safe): information gathering needed; 2 (could be urgent): potential emergency reported; 3 (urgent): emergency under control; 4 (very urgent): immediate response required for a serious emergency.

Search and rescue shifts will be 8 hours long to maintain volunteer satisfaction, with a maximum of 9 shifts during the critical first 72 hours, depending on the situation. The number of volunteers assigned to each of the seven volunteer response centers (1, 4, 9, 10, 11, 13, and 14) per shift will be determined by neighbourhood population density and the urgency level of nearby assembly areas. For instance, the Mogultay district, with 2,548 residents and two disaster assembly areas, has 13 volunteers assigned per response center, or 1 volunteer per 100 people. This volunteer-to-population ratio maximizes the benefit of available volunteers by minimizing potential shortages, with more volunteers allowing for greater regional allocation [44].

Table 4. Volunteer demand, urgency, and duration of work period in the scenarios

	Center Number	Working shift	Total Volunteer	Urgency Level (w_{jt})	Volunteer Demand Range
Scenario 1	7	9	124	4	10
Scenario 2	7	9	124	0 to 4	5 to 44
Scenario 3	2	3	30	3	0 to 15

4.2.3 Scenario 1: Assign an equal number of volunteers for very urgent situations

This scenario aims to equally distribute volunteers across all regions for 9 shifts, prioritizing all volunteer response centers as if they are in the most urgent situation. This approach is designed for the immediate aftermath of a disaster, ensuring maximum utilization of available personnel [45], particularly crucial following large-scale events. For instance, the February 6, 2023, Kahramanmaraş earthquake in Turkey revealed that organizational issues hindered the deployment of search and rescue teams to some districts within the critical first 72 hours, and insufficient personnel caused serious disruptions in certain regions [46].

The proposed model is analysed in 1.073 seconds using the GAMS/CPLEX solver on an Intel i5 11th Gen (2.40 GHz) computer with 8 GB of RAM, based on data in **Table 4. Table S. 2** (see in the Supplementary file) presents work center and period data for the first 20 volunteers. The assignment model is assigned 10 volunteers per period to each response center, with volunteers in (C_1) assigned a maximum of 5 work shifts (including rest periods) and those in (C_4) assigned 4. The model can accommodate additional volunteers if the volunteer pool increases or work hours and regions decrease. To optimize task allocation, meet staffing needs, improve volunteer satisfaction, maintain organizational continuity, and optimize work-rest intervals, volunteers were not assigned to consecutive shifts.

4.2.4 Scenario 2: Volunteer needs and urgency change over time

In this scenario, a real-life disaster impacts specific regions, leading to varying personnel needs and urgency at different times in volunteer centers [47]. The goal is to prioritize volunteers with the highest experience and knowledge based on the emergency level. Additionally, since some centers may not need personnel at certain periods, volunteers will not be assigned to them. To evaluate each region's situation, a minimum number of volunteers will be assigned to each response center initially, with subsequent volunteer distribution based on the disaster's impact in each area.

The data from Scenario 1 will be used as is, with a minimum of 3 volunteers assigned to each region initially. Personnel will be assigned to each region in the first period to examine the situation in the region and determine the urgency level of the response center. Subsequently, volunteers will be located based on regional urgency (from 0 not needed to 4 very urgent) and minimum personnel needs. **Table 5**, designed for scenario 2, is given below. The values in each period's column indicate each center's demand and urgency status. (For instance, in the 2nd period, 44-4 in the 3rd column represents center 9 requesting 44 volunteers with 4 critical emergency codes.)

Table 5. Volunteer needs and urgency levels of response centers for each period.

Cent er	Period								
	1	2	3	4	5	6	7	8	9
1	3-1	0-0	0-0	0-0	0-0	0-0	13-4	13-4	13-4
4	3-1	0-0	0-0	0-0	0-0	0-0	13-4	13-2	13-1
9	3-1	44-4	44-4	44-4	44-4	44-2	44-2	0-0	0-0
10	3-1	19-4	19-4	19-4	19-4	19-4	0-0	0-0	0-0
11	3-1	17-1	17-1	0-0	0-0	0-0	0-0	0-0	0-0
13	3-1	0-0	0-0	0-0	0-0	0-0	5-4	5-4	5-4
14	3-1	5-1	5-1	0-0	0-0	0-0	0-0	0-0	0-0

***Note:** The numbers separated by dashes in the table represent the urgency and volunteer demand at each center. For instance, in the 2nd period, 44-4 in the 3rd column represents center 9 requesting 44 volunteers with 4 critical emergency codes.

Table 6 presents the volunteer location and period number for each volunteer class obtained with the volunteer assignment model. The results indicate that urgency is prioritised when assessing a center's volunteer request, and efforts are made to assign the highest-level volunteers (c_1), whenever possible. As an example of the first period, the needs of all centers are addressed by volunteers from (c_1). Once all volunteers from this class are assigned, only 3 additional volunteers are assigned from the next class (c_2). During peak periods (2 and 3) of the requested volunteer number, the 10th center's requests are fully met, while the 9th center has two unfulfilled requests. Moreover, the 11th and 14th centers could not be assigned any volunteers due to the lack of urgency. In evaluating the total demands of all centers (517), while the demands of some centers (1, 4, 10, and 13) are fully met, there is a shortage of 63 volunteers (12%) in the others.

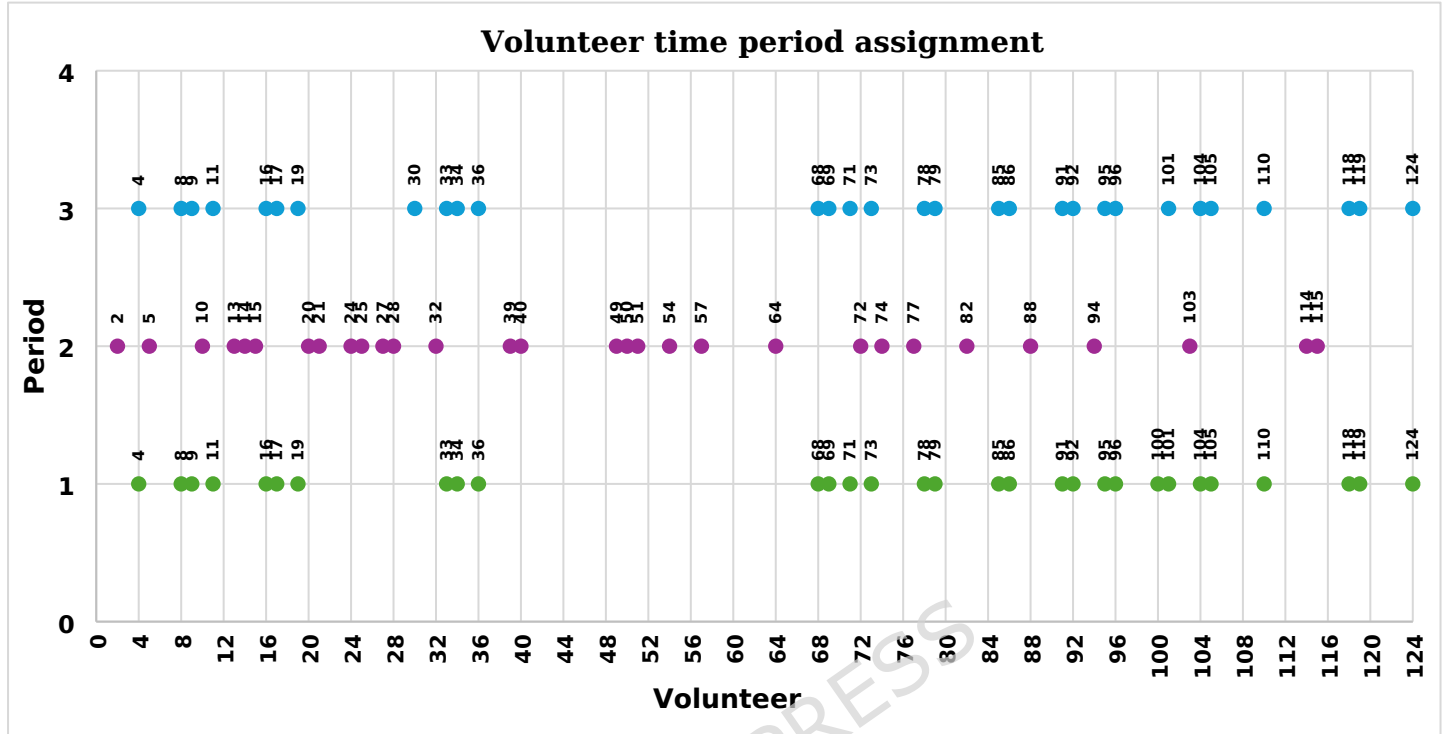
Table 6. Number of volunteers per class assigned to volunteer centers for each period.

	Class (c_i)	Period								
		1	2	3	4	5	6	7	8	9
Center 1	1									
	2									
	3							8	10	
	4	3						5	3	13
	Total	3	0	0	0	0	0	13	13	13
Center 4	1									
	2								1	
	3							4	12	13
	4	3						9		
	Total	3	0	0	0	0	0	13	13	13
Center 9	1		4	6	3	7	4	10		
	2		20	15	21	14	16	33		
	3	1	16	8	17	11	11			
	4	2	4	13		12				
	Total	3	44	42	41	44	31	43	0	0
Center 10	1		2	2	2	2				
	2		7	7	5	9				
	3		10	5	9	2	15			
	4	3		5	3	6	4			
	Total	3	19	19	19	19	19	0	0	0
Center 11	1									
	2									
	3	1								
	4	2								
	Total	3	0	0	0	0	0	0	0	0
Center 13	1									
	2									
	3	1						1	4	
	4	2						4	1	5
	Total	3	0	0	0	0	0	5	5	5
Center 14	1									
	2									
	3									
	4	3								
	Total	3	0	0	0	0	0	0	0	0

4.2.5 Scenario 3: Fulfill the demand for a few volunteers

This scenario applies when a disaster, such as a flood, impacts a small area and necessitates collaboration with a specialized team, requiring fewer personnel [48]. It seeks to effectively assign volunteer duties by selecting the most knowledgeable and experienced individuals for critical tasks that require limited personnel, thereby safeguarding less experienced volunteers from risk. For this purpose, the Atatürk neighbourhood located on the riverbank is selected and the volunteer needs of centers 9 and 10, which are determined as the response center in this region, will be met. As data for our model, 15 personnel will be assigned to each region to meet the most urgent demand. Our model displays the working 3 time periods of volunteers based on the results from the GAMS/CPLEX solver shown in **Figure 6**.

In this scenario, where the need for a small number of volunteers is met in three periods of time. According to the results obtained 14 volunteers (C_4) and 49 volunteers (C_3), in the two classes with the lowest level of experience and knowledge are not assigned any tasks. While 30 volunteers in the (C_2) are assigned to a single period the remaining 9 people from this group and all volunteers of (C_1) are assigned to two different periods. The goal is to efficiently assign volunteer duties while minimizing risks to others by choosing the most knowledgeable



and experienced volunteers, particularly in few-personnel, mission-critical situations.

Figure 6. Working shifts of volunteers assigned for Scenario 3

5. Discussion

This study assigned experienced volunteers to critical areas, matching them to specific response centers based on needs and urgency across shifts. Volunteers were allowed rest periods, working a maximum of one out of every two consecutive shifts. The model's effectiveness was evaluated under varying scenarios, considering diverse needs and urgencies. **Figure 7** illustrates the percentage assignment distribution of volunteer classes across all periods in these scenarios.

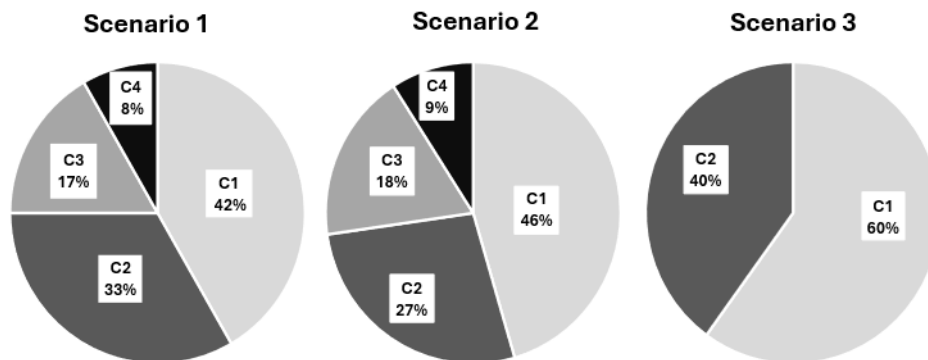


Figure 7. Volunteer assignment percentages based on scenarios

The data indicates that the volunteer assignment model prioritises experts before selecting from other groups, assigning lower-class volunteers as needed after the top-tier volunteers are allocated. Volunteers in class C_1 are assigned more tasks in all scenarios, while those in class C_4 took on fewer or no tasks compared to the other class. In scenarios with low volunteer

needs (Scenario 3), no volunteers are selected from the less experienced groups (C_3 and C_4). When assessing the need for volunteers in various situations, it has been found that if the requirement fits the size of the group C_1 , all volunteers are provided by this group, and the volunteer class order is applied in the assignment.

In Scenario 1, volunteers are assigned tasks to maximize their working time and address urgent personnel needs. The goal is to deliver immediate assistance to all disaster victims across a broad area by evenly distributing the most suitable volunteers to each response center. In Scenario 2, it is believed that a disaster adversely impacts a specific region, leading to secondary disasters later. For instance, an earthquake first affects a particular area, and subsequently, other initially unaffected areas require assistance due to aftershocks. This scenario aims to prioritize emergency areas when personnel shortages arise during disasters. Data shows that assigning the most experienced individuals to the most urgent needs maximizes benefits; however, due to a limited number of volunteers, less urgent regions cannot be adequately staffed and experience volunteer shortages. Scenario 3 is inspired by a regional disaster, like a flood, affecting the riverbed area. The timeframe is short, and the demand for volunteers is minimal. Results show that inexperienced volunteers are not assigned tasks, while all experts participated in the operations.

This model considers relevant disaster scenarios, including earthquakes and floods, along with varying volunteer needs and urgency levels. The criteria for classifying volunteers by disaster type can be adjusted, allowing for varied task assignments within the model. For secondary disasters following the primary event, such as fires or landslides, volunteers can be allocated additional tasks in categories like search and rescue, first aid, or food distribution. The model adjusts working time based on the critical first 72 hours (8-hour shifts) following the most destructive earthquake. For shorter disasters like storms, the study period can be reduced accordingly. The model, while primarily aimed at post-disaster volunteer assignments, can also be applied to volunteer training and drills before a disaster. For instance, considering regional characteristics, less experienced and expert volunteers can be mixed and organized into groups for drills related to previous avalanche disasters, allowing them to gain valuable experience.

5.1 Sensitivity Analysis

To illustrate the model's flexibility, a sensitivity analysis is conducted by varying the number of volunteers and response centers. This verifies the model's robustness and reliability under different conditions. **Table 7** summarizes an analysis examining the effects of varying the number of volunteers, response centers, and their requests, and volunteer rest periods on resolution time, number of variables, and volunteer demand fulfilment rate, demonstrating the model's adaptability. The values in the grey row represent the baseline model, where all values except the parameter being examined are held constant and compared to other models.

Table 7. Sensitivity analysis of volunteer assignment model parameters

Parameter s	Values	Solution time	Changes	Variabl es
Volunteer Numbers	124	1.07		7812
	93(%25 decreased)	0.83	%22 Lack of Volunteer	5859
	155(%25 increased)	1.15	Not used 15 Volunteer in C_4	9765
Response Center Demand	10	1.07		7812
	5(%50 decreased)	1.03	Not used in C_4 , only use 9 Volunteer in C_3 .	7812
	15(%50 increased all period)	1.08	Lack of 86 volunteers %69 need more volunteers	7812
	7	1.07		7812
	14 (%100 increased)	2.33	Lack of 156 volunteers %125 need more volunteers	15624

Response Center Number	4(%42 decreased)	0.63	Not used C ₄ , only used 19 volunteers in C ₃	4464
	2	1.07		7812
Consecutive Periods	3	0.74	Need more 110 volunteers % 88	7812
	0	0.51	Not need 54 volunteers (all C ₄ , and 40 C ₃)	7812

When examining the number of volunteers, one of the key constraints in the model, it was found that reducing by 25% to 93 resulted in a volunteer shortage, leaving 22% of response center demand unmet. Conversely, increasing volunteers by 25% to 155 fully met demand, leaving 15 volunteers in class C₄ unassigned. The change in the number of variables (3906) had a negligible impact on solution time, increasing it by approximately 32 seconds.

Volunteer response center demand was halved each shift, no volunteers from the class C₄ were used, while only 9 volunteers from the class C₃ were able to take on the task. When the demand was increased by 50%, it resulted in a shortage of 86 volunteers and required 69% more volunteers. Since the amount of demand did not affect the number of variables, there was almost no difference in solution times.

Considering the 14 disaster relief collection areas identified in the study region (doubling the number of response centers), a shortage of 156 volunteers emerged, necessitating a 125% increase to meet demand. This shortage was identified by examining the change in volunteer response centers where variable number and resolution time showed the most significant differences. Conversely, with only 4 volunteer response centers, C₁ and C₂ volunteers largely met demand, with only 19 C₃ volunteers participating. Tripling the number of variables almost quadrupled the resolution time.

When the constraint of volunteer rest periods is analysed, eliminating rest periods allows for task distribution with 54 fewer volunteers. However, requiring each volunteer to receive a single task in three consecutive periods necessitates an 88% increase in volunteer numbers to meet demand.

Sensitivity analysis revealed that changes in the number of volunteer response centers most significantly impacted the number of variables and solution time of the assignment model. This is primarily because the model's objective function maximizes matching based on the urgency and demand of response centers, which are also prioritized as constraints. While changes in the number of volunteers and consecutive periods don't greatly affect solution time or the number of variables, they can lead to volunteer shortages or excessive workloads in specific skill classes (e.g. C₁) due to unequal volunteer allocation, as the model aims to balance volunteer satisfaction and rest. Varying the number of volunteers and consecutive periods has little impact on solution time or the number of variables; too few volunteers result in shortages. Conversely, too many volunteers lead to unequal task distribution, with some classes overworked (e.g. C₂) and others idle (e.g. C₄). More consecutive periods in rests hinder the ability to meet volunteer demand, while no rest periods create task imbalances, preventing lower-class volunteers from being assigned tasks.

5.2 Managerial Insights:

This study contributes to emergency volunteer management by presenting a two-stage assignment model. This model prioritizes volunteer satisfaction by matching expert volunteers to critical areas, considering the urgency of needs. The first stage strategically identifies response centers based on population density for effective and timely intervention. The second stage uses a skill-based allocation model, matching volunteer expertise to regional criticality, ensuring optimal task allocation across diverse disaster scenarios. The study offers significant academic and practical implications.

- This model adopts a two-stage approach to disaster preparedness and volunteer management: first, contributing to the disaster preparedness phase by assessing location suitability and identifying an optimal number of volunteer response centers, and providing drill and training opportunities in these areas; second, maximizing the effectiveness of personnel by assigning tasks to volunteers during disaster response. This separation simplifies the process compared to a single, complex model and contributes separately to two different areas (preparation and response) in disaster management.
- Adapting the assignment model to mirror earthquake disaster response, particularly volunteer management within personnel management, enhances preparation and response phases. This model was applied to a volunteer search and rescue community, contributing to the division of labour in volunteer management.
- Selecting volunteer response centers from easily accessible, safe, and convenient disaster collection areas nearest the disaster zone enhances volunteer safety and post-disaster assistance. Because these areas are located in densely populated, easily accessible, and safe locations identified through expert research, choosing response centers from them provides regional access, ensures volunteer safety near victims, and facilitates task distribution.
- Strategic task allocation before and after disasters ensures rapid response and maximizes personnel resources. A planned, needs-based system prevents critical needs from being unmet due to personnel shortages or a lack of defined tasks.
- The flexible two-stage volunteer assignment model, which addresses both location and task allocation, applies to various disaster management scenarios and can be implemented by diverse institutions and organizations for task allocation, volunteer training, and other purposes.
- This assignment model prioritizes matching tasks to volunteers based on their knowledge and experience. It maximizes the effective use of expertise by ensuring that the most experienced volunteers handle urgent and specialized tasks. As seen in Scenario 3, where all expert C_1 volunteers were assigned tasks, while only 30 C_2 volunteers were needed, and no other groups were used due to low demand. This approach reduces the risks of dissatisfaction, volunteer turnover, or task failure by preventing critical tasks from being assigned to inexperienced volunteers.
- In disaster management, volunteers are crucial. To maximize their impact and ensure continued service, volunteer satisfaction is key. An assignment model that divides tasks into periods, limits consecutive tasks, and incorporates rest periods, up to 5 shifts out of 9, increases volunteer commitment and satisfaction by preventing excessively long working hours. For example, inexperienced volunteers (C_3) work only 3 shifts during periods of low demand.

6. Conclusion

In the paper's initial phase, suitable areas for volunteer work are identified. These areas are selected based on safety and accessibility criteria to ensure an optimal working environment. Then develop a volunteer assignment model that pairs the most knowledgeable and experienced volunteers with the highest-priority needs. This model is designed to be flexible, maximizing the effectiveness of volunteer contributions while adapting to various scenarios. It also ensures that volunteers have adequate rest periods outside of their working hours.

The initial model stage assessed population densities as demand across disaster collection areas. Considering distances, it selected 7 optimal volunteer response centers from 14 candidate collection areas by P Median. This aims to balance volunteer placement, avoiding excessive centers that increase travel times and too few, which would cause overcrowding given capacity limits.

The second stage of the proposed volunteer assignment model results indicate that during low demand, volunteers from other groups are only assigned after all experienced volunteers have been allocated. For instance, in the low-demand Scenario 3, only expert and experienced

volunteers were assigned tasks. This strategy focuses on assigning less experienced volunteers to lower-risk tasks rather than to critical ones. In the more-demand scenario, expert volunteers worked 5 out of 9 shifts, while less experienced volunteers worked 4 shifts to meet staffing needs. In contrast, when demand surpasses the available volunteer numbers, some centers are inadequately staffed since urgent needs are prioritized during emergencies. In Scenario 2, high-priority centers (e.g., 10 and 13) were fully staffed during peak demand (e.g., 2-3 shifts), while lower-priority areas (e.g., level 1, center 11) experienced a shortage of 63 volunteers over 9 shifts. The model distributes volunteers fairly, even if it results in shortages, and accounts for rest periods when immediate post-disaster support is required. The number of volunteers here can be adjusted based on specific center requests and desired periods.

To evaluate the model's real-world applicability, a disaster and emergency relief volunteer group was selected. This group, which aimed to raise disaster awareness and expand the volunteer base through community training, consisted of 124 members throughout the study, providing a suitable small-scale test case. Furthermore, because the volunteer group was in areas accessible to disaster response centers, the scenarios were designed as real-world disaster simulations. The existence of a practical application example allows the model to demonstrate its potential for adaptation to various volunteer organizations operating in different fields.

The study has several limitations. The small size of the research area, low population density, and limited volunteer pool prevent the model from demonstrating its application and ability to handle the complex structures typical of large volunteer activities. It is recommended that the model be applied to organizations operating in diverse fields with more volunteers covering broader regions. Although the model is designed around a two-stage volunteer placement task distribution, it uses a single objective function, ignoring some constraints found in volunteer assignment problems. Including the following constraints would allow for a more comprehensive study, enhancing the model's applicability and effectiveness:

- Volunteers' location and time preferences.
- Penalties for a shortage of volunteers.
- Transportation time required for volunteers to reach designated areas.
- Different tasks and the ability of volunteers to perform these tasks.
- Budget constraints, including daily expenses for food and transportation.

Future research could apply the set covering problem to more effectively identify volunteer response centers. While designing real-life disaster scenarios is challenging due to their unpredictable and uncertain nature, simulation techniques can generate various scenarios for model development. The volunteer group classification used in the volunteer assignment model can be addressed using existing literature. A new two-stage assignment model could be developed, using artificial neural networks instead of TOPSIS for classifying volunteers by knowledge and skill level in the first stage.

DECLARATIONS

Conflict of interest

The authors declare that they do not have conflict of interest.

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